Exploring the wakes of large offshore wind farms

S Emeis[1], S Siedersleben[1], A Lampert[2], A Platis[3], J Bange[3], B Djath[4], J Schulz-Stellenfleth[4] and T Neumann[5]

[1] Karlsruhe Institute of Technology, Garmisch-Partenkirchen, Germany
[2] Technical University of Braunschweig, Braunschweig, Germany
[3] University of Tübingen, Tübingen, Germany
[4] Helmholtz Centre Geesthacht, Geesthacht, Germany
[5] UL International GmbH, Wilhelmshaven, Germany

stefan.emeis@kit.edu

Abstract. Offshore meteorological characteristics set specific conditions for the operation of offshore wind farms. One specific feature is low turbulence intensity which on the one hand reduces loads on turbines but on the other hand is the reason for much longer turbine and farm wakes than over land. The German Government is presently funding a research project called WIPAFF (WInd PArk Far Field) which heads for the analysis of properties and impacts of offshore wind park far fields. The focus is on the analysis of wind farm wakes, their interaction among each other and their regional climate impact. This is done by in-situ, extensive aircraft and satellite measurements and by operating meso-scale wind field models and an analytical wind farm model.

1. Specific meteorological conditions for offshore wind farms

The marine atmospheric boundary layer (MABL) offers specific meteorological conditions for the operation of offshore wind farms. Amongst these conditions are availability of large continuous areas for very large farms, higher mean wind speeds, lower turbulence intensity, and less vertical wind shear over the rotor plain due to the low roughness of the sea surface. This leads to higher electrical energy yields and lower fatigue loads on the turbines [1].

But the lower turbulence intensity does not have advantageous effects only. Turbulence is an important parameter for the dissipation of wakes as well. Higher turbulence helps to dissipate turbine and farm wakes rapidly [2]. Therefore, wakes behind offshore wind turbines and wind farms are expected to be much longer than behind onshore wind turbines and farms (see e.g., [3]). Numerical modelling with simple analytical wind park models [4] and meso-scale wind field models [5] have shown these prolonged wind farm wakes as well. Wake lengths up to about 100 km have been modelled [5].

The different temporal variations of atmospheric stability in the MABL compared to onshore sites are another feature of offshore areas chosen for wind energy generation. Offshore thermal stability mainly varies in an annual course due to the overall temperature difference between the sea water and the MABL air temperature [6] and also due to moving depressions [7]. The diurnal variation of stability which is very prominent at onshore sites is nearly completely absent offshore and only happens in reduced form when the wind is directly blowing from the land [8].

In Europe, many countries have started to erect offshore wind farms in the North Sea. This planned intensive usage of the North Sea for offshore wind farms poses several questions which deserve answers in the near future. Amongst these questions are: (1) how far will wakes extend behind wind farms? (2) how do the extension of wakes depend on atmospheric conditions such as thermal stability and sea surface conditions? (3) will the wakes from different wind farms interact which each other? (4) can these wakes be adequately modelled with meso-scale wind field models and other wind farm models? (5) will there be an impact of the planned wind farms on the regional climate at adjacent coastal areas?

In order to find these answers the German research project WIPAFF (WInd PArk Far Field) has been initiated within which aircraft measurements, SAR satellite image evaluation and numerical modelling will form a major part. After a short look back on earlier wake measurements by aircraft in Section 2, we will present the principal outline of the WIPAFF project in Section 3 and will give a brief outlook in Section 4.

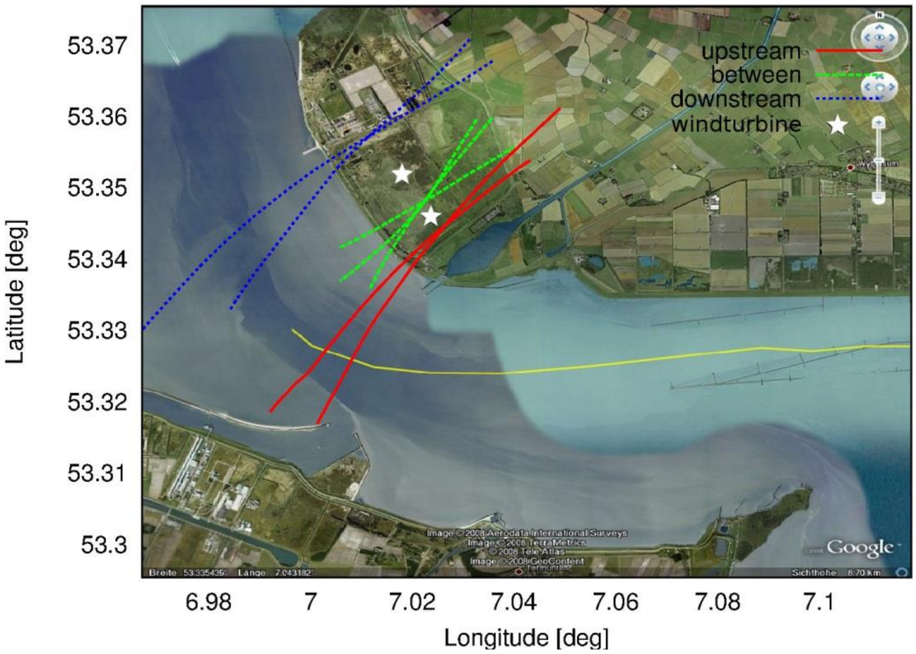

Figure 1. Tracks of flights with the Helipod measurement system upstream (red), in between (green) and downstream (blue) of two large wind turbines at the German coast near Emden (marked by white stars). The flights were performed in May, 2008, perpendicular to the mean wind vector.

2. Preliminary study of wind-turbine wakes

In May, 2008, a first (very short) in-situ flight experiment was performed in order to prove that wind-turbine wakes can quantitatively be observed using research aircraft. The experiment was carried out at the north-western German coast, near the city of Emden, using the helicopter-borne turbulence probe Helipod [9]. The flight tracks of 1 to 2 km length (Figure 1) were orientated perpendicular to the mean wind (coming from eastern to southeastern directions, between 100 and 110 degree) upstream, downstream and in between two large wind turbines. The two Enercon-126 turbines were installed close to the flat coast and had a hub height of 135 m and rotor blades of 63 m length (resulting in an over-all height of 198 m).

Figure 2 shows the measured turbulent kinetic energy (TKE) along the flight paths. TKE is the sum of the three wind component variances times the air density and divided by 2. The Helipod was flown with a constant airspeed of 40 m/s, resulting in a time scale below one minute for one flight leg. Within one minute flight time for one leg, Taylor's hypothesis of frozen turbulence [10] is fulfilled. Therefore, these measurements can be considered as an instantaneous snapshot. Upstream, TKE is larger over land (right hand site of diagram a)), since the surface roughness induces turbulence mechanically. In between the two turbines, turbulence is increased drastically. But also downstream, the TKE is large, indicating a wake travelling over the open water of the Dollart bight towards the Dutch coast (left hand side of diagram c)). The data was gathered during one flight only. Any changing boundary conditions like wind direction or speed, thermal stratification, water-wave height etc. cannot be studied from this data. Thus the Emden data set lags significance on one hand, on the other hand it demonstrates that turbine wakes are easily identified in airborne data, and can be quantified regarding strength and dispersal direction.

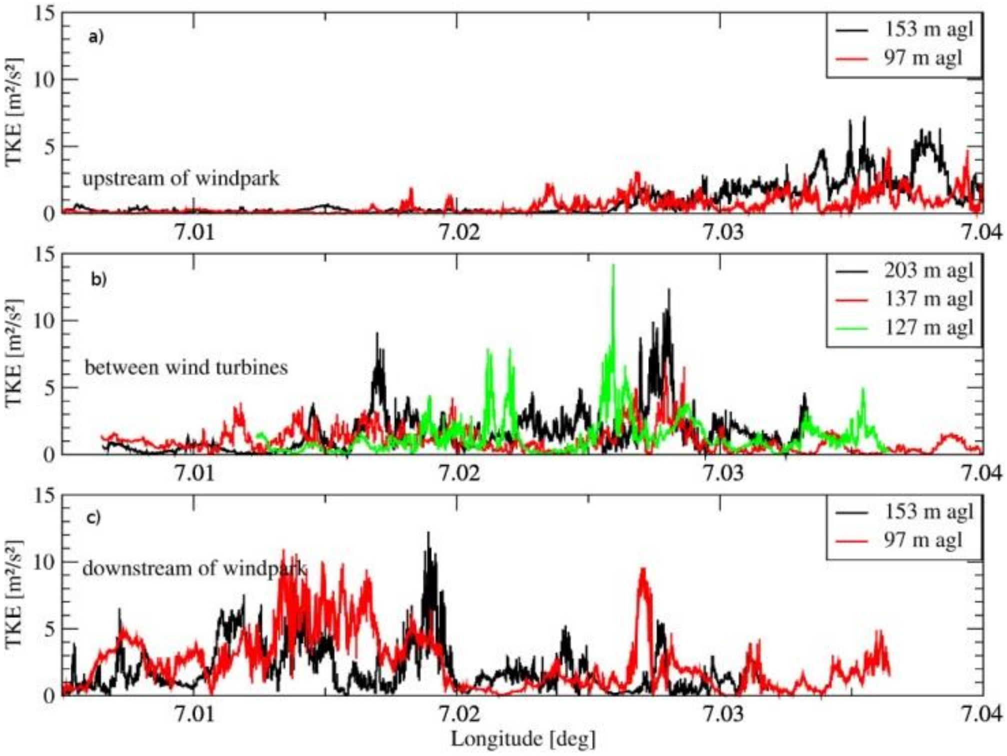

Figure 2. TKE measured during the Helipod flights at two wind turbines near Emden in May, 2008 (see Fig. 1). The diagrams show data a) upstream of the turbines, b) in between the two turbines and c) downstream of the turbines at different flight levels about ground level (agl).

3. The WIPAFF project

The project WIPAFF is a common effort of five institutions headed by the Institute for Meteorology and Climate Research of the Karlsruhe Institute of Technology in Garmisch-Partenkirchen. The partners are from the University of Braunschweig, the Helmholtz Centre Geesthacht, UL International GmbH (DEWI) in Wilhelmshaven and the University of Tübingen. The project is planned to run from November 1, 2015 to October 31, 2018. The focus is on wind and turbulence conditions in far fields of offshore wind farm wakes, i.e., 10 to 100 km behind the wind farms. The analyses and simulations are based on in-situ, extensive aircraft and satellite measurements and on operating meso-scale wind field models and an analytical wind farm model.

3.1. Wind field simulations

Numerical modelling in this project will rely on the meso-scale wind field model WRF [11]. WRF will be updated with a wave model WAM [12][13] and an appropriate parameterization scheme that describes offshore wind farms. Then the whole updated model is tested and validated with SAR, in-situ and aircraft data from the project (see following subsections). Finally, industrial wind models [14] and an existing simple analytical wind farm model [4] are validated and optimized (if possible) by comparison to the WRF results and the experimental data.

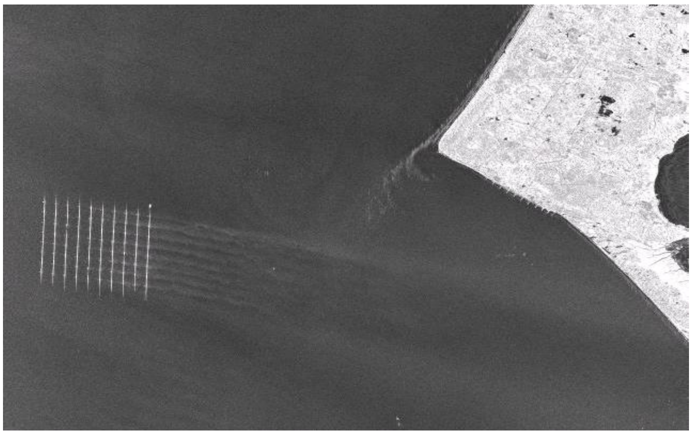

Figure 3. TerraSAR-X image acquired over the Horns Rev I Windfarm at the Danish west coast on Feb 16, 2012 at 17:10 UTC. The image is a 30 by 20 km subscene of a stripmap data set taken in HH polarisation (©DLR 2012).

3.2. SAR satellite data

Synthetic Aperture Radar (SAR) satellite images for the whole North Sea will be analyzed in this project. The SAR data allow for a determination of the near surface wind speed and the detection of spatial gradients in these near-surface wind fields [15]. The wind fields in these observed wakes can then be compared to the model results and the aircraft measurements. The usability of SAR images to detect wind farm wakes has been proven for the first time in [16]. First comparisons between SAR images and WRF simulations have been shown in [17].

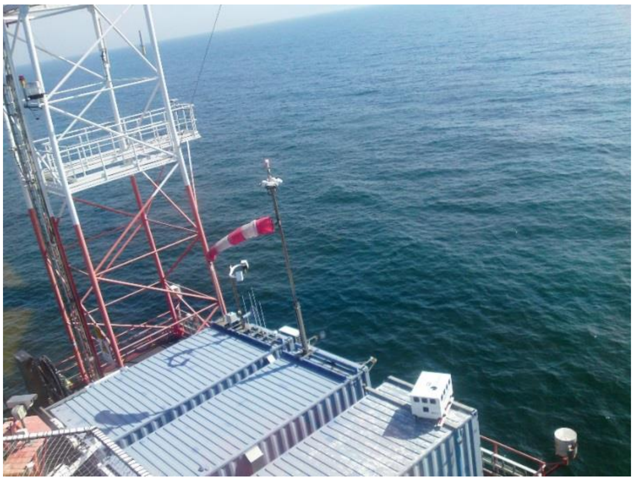

Figure 4. A Windcube (Leosphere) positioned (bottom right) on the FINO1 platform.

Within the WIPAFF project data from both the German satellite TerraSAR-X and the European satellite SENTINEL-1 will be analysed. The required algorithms to convert the sea surface roughness information provided by SAR data into wind speed estimates will be tailored to the specific research questions addressed in WIPAFF. As an example Figure 3 shows a TerraSAR-X scene (©DLR) acquired over the Danish offshore wind farm Horns Rev 1 with clear wake structures east of the turbines.

3.3. *In situ and aircraft measurements*

The measurements in the project comprise wind lidar observations from a platform in the North Sea and extensive aircraft flights on different flight patterns above and behind the wind farms. Wind lidar observations from a platform in the North Sea (such as those, e.g., described in [18]) will provide continuous measurements of vertical wind profiles. Figure 4 shows, for example, a lidar (Windcube, Leosphere) currently positioned on the FINO1 platform.

Figure 5. The research aircraft Do-128 D-IBUF of TU Braunschweig is equipped with a nose boom for meteorological measurements. The laser scanner is located in the cabin, looking downward (Photo: Uwe Bethke).

The aircraft operations are performed with the Do-128 of TU Braunschweig (Figure 5). The flights deliver wind, turbulence, temperature, surface temperature and humidity data at high resolution, like those documented in [19], [20]. The aircraft is equipped with different slow and accurate as well as fast sensors, described in [21]. Additionally, a laser scanner is integrated for the project to determine surface properties, and especially wave profiles. The suitability of the system, providing enough backscatter signals from the water surface with low reflectivity, was confirmed already during a test flight. The flight patterns are determined in accordance with the needs of all partners to be able to use the data for inter-comparison and for the validation of models.

3.4. *Implications for wind farm planning*

Implications for the erecting of larger wind farm clusters will be analysed in the project as well. Large offshore wind farms are expected to influence each other, if they are arranged along the main wind direction. Most wake interaction studies have so far concentrated on turbine wake interactions within a wind farm [3], because clusters of wind farms were rare. A most recent example of such studies can be found in [22]. A first numerical study on wind farm wake interaction can be found in [23].

Wake lengths will depend on atmospheric stratification, because atmospheric turbulence is a clear function of atmospheric stratification. Longer wakes are expected for stable stratification [3], i.e. warmer air over colder water. Figure 6 displays an analysis of FINO1 data from 2005 which demonstrates a clear correlation between wind direction and atmospheric stratification in the North

Sea. Stable situations are coupled to the main wind direction (South-West). Such correlation is assumed to be typical for the two temperate latitude west-wind belts on both hemispheres of the globe, because the correlations are caused by the usual sequence of warm sectors winds followed by cold sector winds of eastward moving depressions. On the northern hemisphere, warm sector winds most frequently come from Southwest and cold sector winds from Northwest. On the southern hemisphere warm sector winds usually come from Northwest and cold sector winds from Southwest. Figure 7 shows a possible array of wind farms on the northern hemisphere which takes into account the correlation shown in Figure 6. Distances between single turbines within wind farms and between entire farms are larger along the most frequent direction of warm sector winds (from Southwest to Northeast) and they are shorter along the perpendicular direction of cold sector winds.

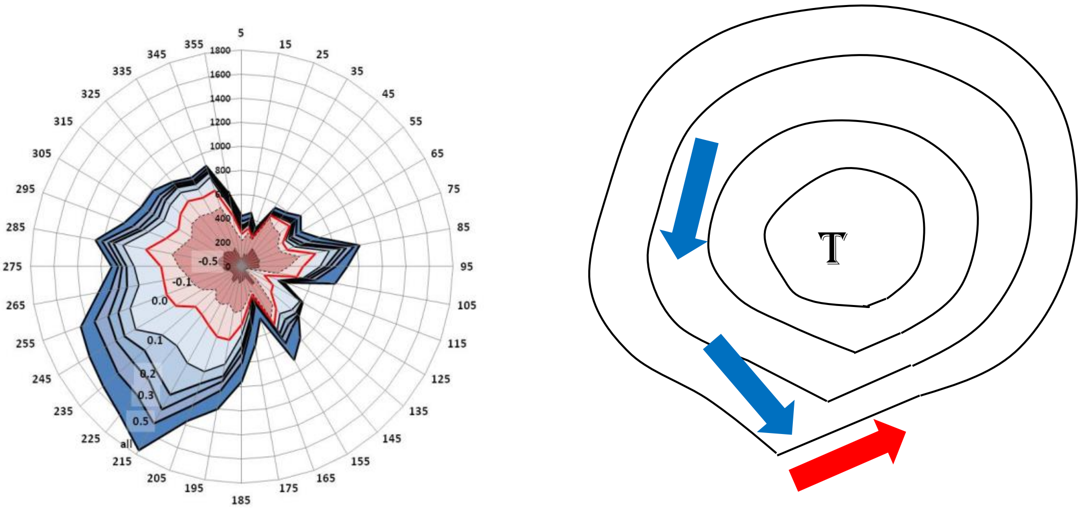

Figure 6. Left: Wind rose indicating the frequency of atmospheric stratifications. Blue: stable stratification, brown: unstable stratification, red line: neutral stratification. Numbers give the stability measure *z/L* with the height above ground, *z*, and the Monin-Obukhov length, *L*. Data displayed are from FINO1 in 2005 at 60 m height, only data between 5 m/s and 25 m/s wind speed have been considered. Right: Schematic of a mid-latitude cyclone on the Northern hemisphere. Red arrow: warm air advection in the warm sector of the cyclone, blue arrows: cold air advection behind the cold front.

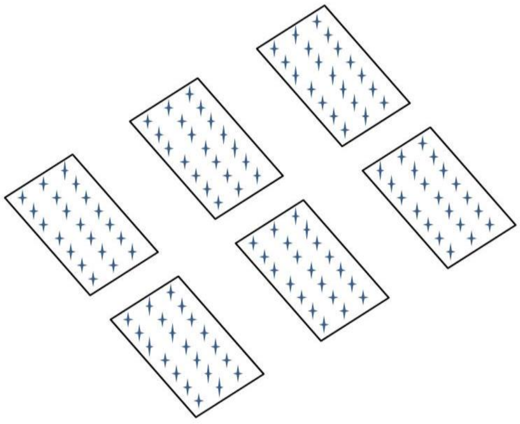

Figure 7. Schematic of a wind farm cluster adapted to the wind conditions shown in Figure 6. Boxes symbolize entire wind farms, crosses within the boxes single turbines. The geographic orientation is identical to the one in Figure 6 (North is at the top).

3.5. Impact on regional climate

Large offshore wind farms are expected to change the downwind local and regional climate, because they slow down the wind speed, produce additional turbulence and mixing, and may cause alterations in cloud and rain formation. Most studies so far have concentrated on larger-scale and global impacts by numerically simulating the impacts of hypothetic large wind parks, e.g., [24][25][26]. Regional impact on surface temperatures has been assessed, e.g., from model simulations in [27] or from satellite surface temperature measurements in [28], and on precipitation from model simulations, e.g., in [29]. A first numerical study focusing on impacts of North Sea wind farms has been published recently [30].

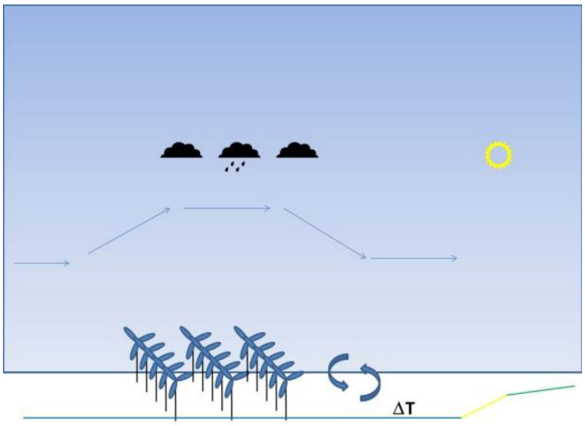

Figure 8. Schematic of the impact of large wind farms or wind farm clusters on the local and regional climate. Thin straight arrows indicate the stream flow, clouds and rain the possible enhancement of cloud formation and precipitation, the two bended arrows enhanced turbulence intensity in the wake.

Figure 8 shows schematically the possible impact from a large wind farm cluster. Reduced wind speed within large wind farms forces the air to rise. This may lead to enhanced cloud formation over the wind farms and possibly even to precipitation formation. Turbulence behind the wind farms will slightly change near-surface temperature in case of non-neutral thermal stratification of the MABL.

The opposite issue, i.e., the impact of climate change on the generation of torque from the wind is not addressed in the WIPAFF project but has recently been addressed in [31].

4. First Results and Outlook

The WIPAFF project has started at the end of 2015. A first test flight over the North Sea took place on April 22, 2006 and passed about 10 km off the downstream side of the wind farm cluster north of Helgoland. Due to the very unstable weather conditions (the stability parameter formed from hub height and Monin-Obukhov length was close to -1) no farm wake was discernable from the data. The absence of a longer wake was confirmed by WRF [11] wind field simulations for that day (not shown) and fits to results from the analytical model [4]. The next flights are planned for September 2016.

Work on the SAR satellite image analysis started with the creation and implementation of the Geophysical Model Function (GMF) for X band radar data following, e.g., [32], thereby eliminating some errors in this reference. A GMF function describes the normalized radar backscatter cross section (NRCS) as a function of wind speed, wind direction (relative to the movement of the satellite) and incident angle of the radar beam at the sea surface (Fig. 9). A sample analysis using such a newly derived GMF of a SENTINEL-1 SAR image is displayed in Fig. 10. Several wind farms in the North

Sea can be clearly identified by reduced wind speeds (e.g., Horns Rev off the Danish coast) and partly also by longer wakes behind them (e.g., Butendiek off the island of Sylt).

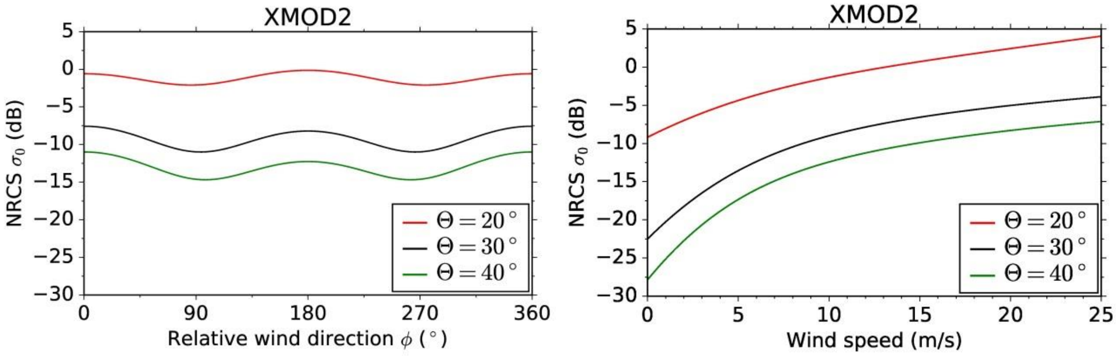

Figure 9. GMF function for X band data from the TerraSAR-X satellite. Left: NRCS as function of wind direction for three incident angles Θ and a wind speed of 10 m/s. Right: NRCS as function of wind speed for a relative wind direction of 45°.

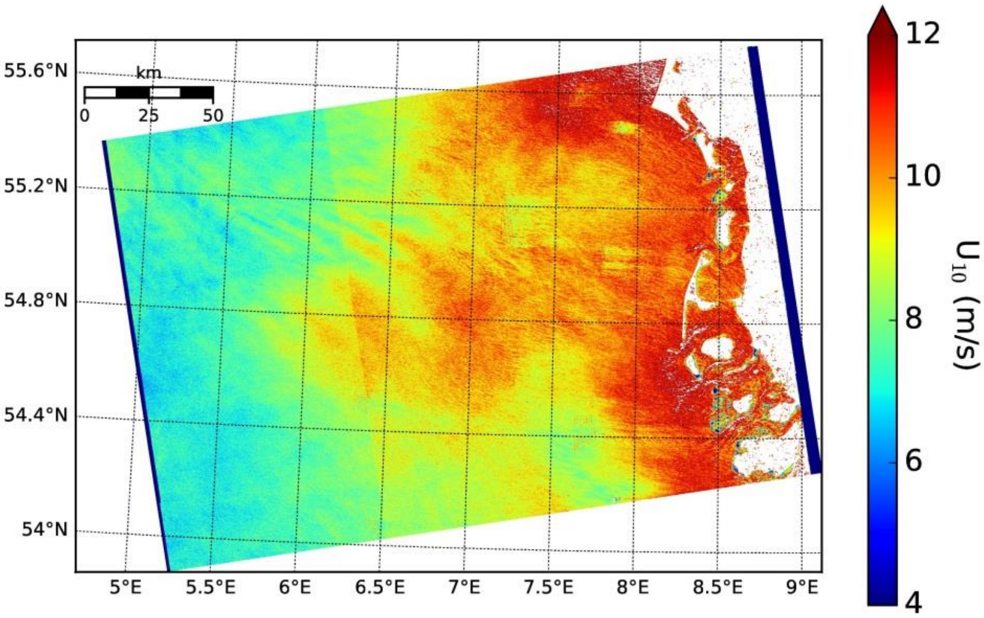

Figure 10. 10 m wind field derived from a SENTINEL-1 wide swath SAR scene using the derived GMF function for the North Sea on June 3, 2015, 17:16 UTC. Wakes of several wind farms are visible, most pronounced those of Horns Rev (near the upper right corner) and Butendiek (west of the island of Sylt).

Numerical modelling has started by coupling the wave model WAM [12] to a WRF model [11]. An iterative procedure of running WRF first, then executing WAM with the wind data from WRF and finally running WRF again with updated roughness data from WAM allows for wind field simulations which take into account the effect of the wind park wakes on the wave field. A first simulation for

May 3, 2006 is displayed in Fig. 11. This time (compared to the first test flight on April 22, 2016) the thermal stratification of the marine boundary layer was very stable and long wakes formed behind the cluster of wind farms north of Helgoland, Butendiek west of Sylt and Dan Tysk even further to the Northwest. Wind direction is slowly turning during the simulation period and at 1300 UTC the wind farm Dan Tysk is in the wake of the wind farm cluster north of Helgoland. According to this simulation, the incoming flow at Dan Tysk is reduced by five to ten percent for several hours.

The results of this project will help to accompany the further deployment of wind farms in coastal areas in any part of the world. The optimized and verified models can be used to calculate and to predict the effect of various offshore scenarios to give insight into optimal planning solutions. The impact on local climatology that might be affected by wind farms will also be assessed based on the model results.

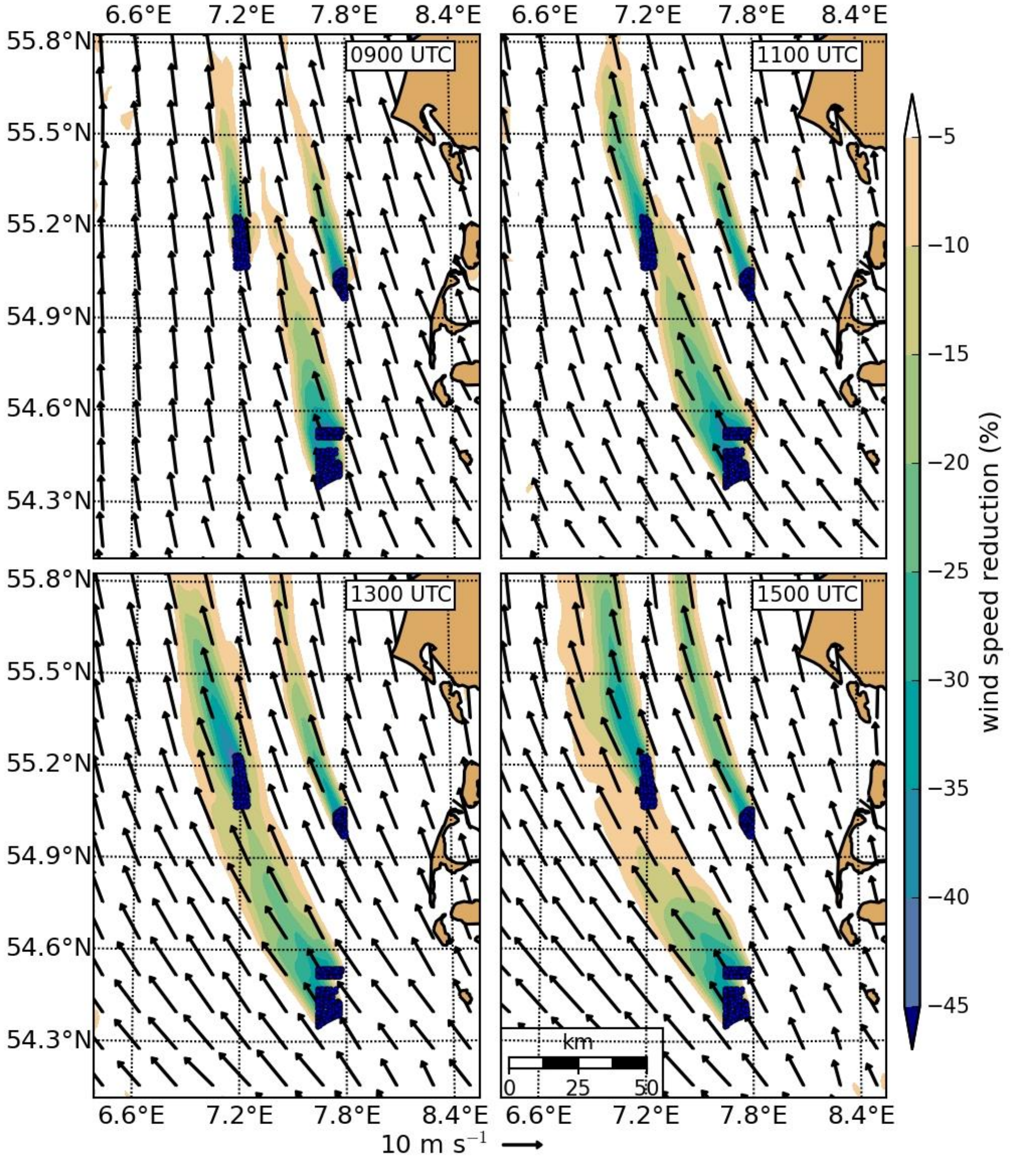

Figure 11. Hub height wind speed reduction (in %) behind a cluster of wind farms north of Helgoland, Butendiek west of Sylt and Dan Tysk even further to the Northwest (dark blue areas) from a WRF/WAM simulation for May 3, 2006 at 9, 11, 13, and 15 UTC. The images show a detail from a larger simulation domain. The horizontal grid resolution is 1.6 km.

5. Acknowledgement

The WIPAFF project is funded by the German Federal Ministry of Economic Affairs and Energy (grant number: FKZ 0325783) on the basis of a decision by the German Bundestag. TerraSAR-X data were provided by DLR in the framework of the TerraSAR-X Science AO COA3120 (WIPAFF_TSX).

6. References

[1] Henderson AR, Morgan C, Smith B, Sørensen HC, Barthelmie RJ and Boesmans B 2003 Offshore Wind Energy in Europe - A Review of the State-of-the-Art *Wind Energy* **6** 35-52

[2] Wu Y-T and Porté-Agel F 2012 Atmospheric Turbulence Effects on Wind-Turbine Wakes: An LES Study *Energies* **5** 5340-5362

[3] Barthelmie R, Frandsen ST, Réthoré PE, Jensen L 2007 Analysis of atmospheric impacts on the development of wind turbine wakes at the Nysted wind farm *Proc. Eur. Offshore Wind Conf. 2007*, Berlin 4.-6.12.2007

[4] Emeis S 2010 A simple analytical wind park model considering atmospheric stability *Wind Energy* **13** 459-469

[5] Fitch AC, Olson JB, Lundquist JK, Dudhia J, Gupta AK, Michalakes J, Barstad I 2012 Local and mesoscale impacts of wind farms as parameterized in a mesoscale NWP model *Mon Wea Rev* **140** 3017–3038

[6] Coelingh JP, van Wijk AJM and Holtslag AAM 1996 Analysis of wind speed observations over the North Sea *J Wind Eng Industr Aerodyn* **61** 51-69

[7] SethuRaman S, Riordan AJ, Holt T, Stunder M and Hinman J 1986 Observations of the Marine Boundary Layer Structure over the Gulf Stream during a Cold Air Outbreak *J Climate Appl Meteor* **25** 14-21

[8] Motta M, Barthelmie RJ and Vølund 2005 The Influence of Non-logarithmic Wind Speed Profiles on Potential Power Output at Danish Offshore Sites *Wind Energy* **8** 219-236

[9] Bange, J., R. Roth, 1999: Helicopter-Borne Flux Measurements in the Nocturnal Boundary Layer Over Land - a Case Study. *Boundary-Layer Meteorol* 92, 295–325.

[10] Wyngaard J, Clifford S 1977 Taylor's hypothesis and high frequency turbulence spectra *J Atmos Sci* **34** 922–927

[11] Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Wang W and Powers JG 2005 A description of the Advanced Research WRF version 2 *NCAR Technical Note TN-468+STR 88* [Available from NCAR, P. O. Box 3000, Boulder, CO 80307].

[12] Monbaliu J, Padilla-Hernández R, Hargreaves JC, Carlos Carretero Albiach J, Luo W, Sclavo M and Güntherd H 2000 The spectral wave model, WAM, adapted for applications with high spatial resolution *Coastal Engineering* **41** 41–62

[13] Staneva, J., A. Behrens, K. Wahle, 2015 Wave modelling for the German Bight coastal-ocean predicting system. In: 4th International Conference on Mathematical Modeling in Physical Sciences (IC-MSquare2015). IOP Publishing Journal of Physics: Conference Series **633**, 012117 DOI: 10.1088/1742-6596/633/1/012117

[14] Barthelmie RJ, Pryor SC, Frandsen ST, Hansen KS, Schepers JG, Rados K, Schlez W, Neubert A, Jensen LE and Neckelmann S 2010 Quantifying the Impact of Wind Turbine Wakes on Power Output at Offshore Wind Farms *J Ocean Atmos Technol* **29** 1302-1317

[15] Koch W and Feser F 2006 Relationship between SAR-derived wind vectors and wind at 10-m height represented by a mesoscale model *Mon Wea Rev* **134** 1505-1517

[16] Christiansen M B and Hasager C B 2005 Wake effects of large offshore wind farms identified from satellite SAR *Remote Sens Environ* **98** 251-268

[17] Hasager CB, Vincent P, Husson R, Mouche A, Badger M, Peña A, Volker P, Badger J, Di Bella A, Palomares A, Cantero E and Correia PMF 2015 Comparing satellite SAR and wind farm

wake models *Journal of Physics: Conference Series* **625** 012035

[18] Peña A, Gryning S-E and Floors RR 2015 Lidar observations of marine boundary-layer winds and heights: a preliminary study *Meteorologische Zeitschrift* **24** 581-589

[19] Bange J, Beyrich F and Engelbart DAM 2002 Airborne Measurements of Turbulent Fluxes during LITFASS-98: A Case Study about Method and Significance *Theor Appl Climatol* **73** 35–51

[20] Bange J, Zittel P, Spieß T, Uhlenbrock J and Beyrich F 2006 A New Method for the Determination of Area-Averaged Turbulent Surface Fluxes from Low-Level Flights Using Inverse Models *Boundary-Layer Meteorol* **119** 527–561

[21] Corsmeier U, Hankers R, and Wieser A. 2001 Airborne turbulence measurements in the lower troposphere onboard the research aircraft Dornier 128-6, D-IBUF. *Meteorologische Zeitschrift* **10** 315-329

[22] Kuo JYJ, Romero DA, Amon CH 2015 A mechanistic semi-empirical wake interaction model for wind farm layout optimization *Energy* **93** 2157-2165

[23] van der Laan MP, Hansen KS, Sørensen NN and Réthoré PE 2015 Predicting wind farm wake interaction with RANS: an investigation of the Coriolis force *Journal of Physics: Conference Series* **625** 012026

[24] Keith DW, deCarolis JF, Denkenberger DC, Lenschow DH, Malyshev SL, Pacala S, Rasch PJ 2004 The influence of large-scale wind power on global climate *PNAS* **101** 16115–16120

[25] Wang C, Prinn RG 2010 Potential climatic impacts and reliability of very large-scale wind farms *Atmos Chem Phys* **10** 2053–2061

[26] Barry DB, Kirk-Davidoff DB 2010 Weather response to a large wind turbine array *Atmos Chem Phys* **10** 769–775

[27] Baida Roy S, Traiteur JJ 2010 Impacts of wind farms on surface air temperatures *PNAS* **107** 17899–17904

[28] Zhou L, Tian Y, Baida Roy S, Thorncroft C, Bosart LF, Hu Y 2012 Impacts of wind farms on land surface temperature *Nature Climate Change* **2** 539-543

[29] Fiedler BH, Bukovsky MS 2011 The Effect of a Giant Wind Farm on Precipitation in a Regional Climate Model *Environ Res Lett* **6** 045101

[30] Boettcher M, Hoffmann P, Lenhart H-J, Schlünzen KH and Schoetter R 2015 Influence of large offshore wind farms on North German climate *Meteorologische Zeitschrift* **24** 465-480

[31] Koch H, Vögele S, Hattermann FF, Huang S 2015 The impact of climate change and variability on the generation of electrical power *Meteorologische Zeitschrift* **24** 173-188

[32] Li X-M, Lehner S 2014 Algorithm for Sea Surface Wind Retrieval from TerraSAR-X and TanDEM-X Data *Geoscience and Remote Sensing IEEE Transactions* **52** 2928–2939